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METEOROLOGICAL RESEARCH COMMITTEE

Two-way relationships between the snow/ice limit and 1000-500 mb. thicknesses in the overlying atmosphere

by

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Summary

Statistical studies of 1000-500 mb. thickness (i) with frozen or unfrozen forms of precipitation occurring and (ii) respectively over regions of extensive snow/ice - covered surface, over bare ground and open sea are used to discover relationships between the thickness values prevailing and (i) the likelihood of rain or snow falling (ii) the snow/ice limit on the ground. The results indicate an important influence produced by snowfields of the order of 1,000 miles and more in longitudinal extent upon the general circulation of the atmosphere.

1. Introductory. 1000-500 mb. thickness maps (relative topography) and the associated 500 mb. contours (absolute topography of the 500 mb. surface) have become the main tools of the busy forecaster concerned with co-ordination of much upper air data and of the research analyst studying broad-scale weather patterns. The 500 mb. level is the highest for which enough reliable data are available for analysis over wide areas, and these charts provide a good synopsis for study of the basic thermal and dynamical problems.

The investigation here described was undertaken firstly to establish a readily usable criterion for the forecaster with regard to thickness values and the probability of rain or snow falling, and secondly to probe in more detail an evident association between the 17,400 ft. thickness isopleth and the contemporary limit of snow-cover and of fast ice on the polar seas.

The results suggest that a widespread snow-cover behaves as an important control reacting upon the atmospheric circulation itself.

2. Vertical temperature distribution and 1000-500 mb. thickness. To be able to follow the working of climatic controls we commonly focus our attention on particular thickness isopleths, conveniently marked by standard colours on the working charts, as introduced by Dr. Sutcliffe. Details are given in Table 1.

Table 1. Standard thickness isopleths and corresponding temperatures.

1000-500 mb. Thickness		Corresponding Temp. at 1000mb. (for saturated Adiabatic Lapse Rate throughout)		Standard Colour of Isopleths
Feet	Metres	°C.	°F.	
19,200	5,850	27	81	Purple
18,600	5,670	20	68	Red
18,000	5,490	13	55	Green
17,400	5,310	6	43	Blue
16,800	5,130	- 1.5	29	Brown
16,200	4,940	- 9	16	Purple
15,600	4,760	-16.5	2	Red

/Fig. 1

Fig. 1 presents the distribution of temperatures aloft corresponding to these particular thickness values in certain circumstances:

(i) Full lines - saturated adiabatic lapse rate throughout the 1000-500 mb. layer.

(ii) Pecked lines - dry adiabatic lapse rate from 1000 mb. up to the 850 mb. level, saturated adiabatic lapse rate from 850 to 500 mb.

It will be seen by eye that strong inversions of temperature confined to the surface layer (often with pressures over 1000 mb.) must have little effect on the temperatures above 900 or 950 mb. corresponding to particular thickness values. Larger positive temperature departures in the upper levels from the curves shown in fig. 1 are only likely to occur with deep inversions or isothermal layers - i.e. with a few fronts and occasionally in other situations in continental interior or inner Arctic regions.

In warm climates, where the air may have a high moisture content, temperatures indicated by the curves of state in fig. 1 should be virtual temperatures, exceeding the dry bulb temperature by up to 5°C (9°F) - the figure for saturated air at an observed temperature of 30°C (86°F.). At normal surface temperatures in middle latitudes the correction for virtual temperature is seldom more than 1 to 2°C., and at the freezing point or below the discrepancy is quite negligible.

In order to form a more realistic gauge of the dry-bulb temperatures actually occurring with the particular 1000-500 mb. thicknesses corresponding to our standard lines, all available upper air ascents from stations in western, central and northern Europe and from the weather ships in the eastern north Atlantic for the year 1951 which gave thickness values of just 16,800; 17,400; 18,000 or 18,600 within ± 30 ft. were statistically examined.* The results of this examination are set forth in Table 2.

To reduce the work to manageable proportions, the 18,000 ft. thickness cases studied were limited to those occurring in July, November and December.

/Table 2.

* FOOTNOTE. The stations examined were:-

British ocean weather ships near 59°N 19°W and 52°N 20°W

Thorshavn, Lerwick, Stornoway, Leuchars, Aldergrove, Valentia, Liverpool, Larkhill, Camborne, Downham Market, Sola, Gardermoen, Torslanda, Stockholm, Riga, Warsaw, Copenhagen (Kastrup), Flensburg, Jever, Iserlohn, Hanover, Berlin (Tempelhof), Greifswald, Wernigerode, Dresden, Erlangen, Munich (surface temperatures not used: altitude 1,700 ft.), Wiesbaden, Utrecht (De Bilt), Brussels (Uccle), Paris (Trappes), Strasbourg, Bordeaux, Lyons, Nimes, Payerne (surface temperatures not used: altitude 1,500 ft.), Vienna.

Checking weeded out some doubtful ascents. In the end 293 ascents from these 39 places were used and are summarized in Table 2.

Table 2. Observed Temperatures °F. with particular 1000-500 mb. Thickness values.

1000-500 mb. Thickness ft.	Surface Temps. °F. Mean	S.D.	Extremes	Temps. at 850 mb. °F. Mean	S.D.	Extremes	Temps. at 700 mb. °F. Mean	S.D.	Extremes	Temps. at 500 mb. °F. Mean	S.D.	Extremes	No. of Cases
16,800	25.7	10.3	37 -1	11.3	3.8	+17 + 5	-5.5	2.4	-2 -9	-36.9	5.4	-27 -44	18
17,400	40.1	5.6	52 28	25.5	2.9	33 18	+9.6	2.3	+16 + 3	-18.8	4.2	-10 -28	160
18,000	51.6	6.2	63 33	38.7	2.9	44 32	27.0	2.1	31 21	- 1.1	2.6	+ 4 - 6(July,Nov., Dec. only)	41
18,600	69.7	7.6	84 50	55.5	3.1	64 49	39.7	2.3	45 34	+12.8	3.2	+23 + 5	74

The striking feature of Table 2 is that standard deviations are only about 3°F. at all the upper levels, save for the top of the 1000-500 mb. layer in the coldest ascents. The actual mean temperatures are close to the standard curves in fig. 1.

Many different groupings of the ascents according to time of day, time of year and geographical position were tried. The resulting mean temperatures differed in nearly all cases by less than 2°F. at 500 and 700 mb. and, in most cases, also at 850 mb. from the overall means in Table 2. Greater differences occurred at the ground, but these were entirely obvious. Only the following selected cases (Table 3) were of any special interest.

Table 3. Observed Temperatures °F. in selected situations.

1000-500 mb. Thickness ft.	Mean Temp. at Ground °F.	Mean Temp. at 850mb. °F.	Mean Temp. at 700mb. °F.	Mean Temp. at 500mb. °F.	No. of Cases	Basis of selection	
16,800	18.3	9.1	- 4.7	- 33.4	9	Continental group	Stockholm Torslanda Oslo
16,800	31.0	13.4	- 6.4	- 40.4	9	Oceanic Group	Ships Thorshavn Lerwick Stornoway
17,400	44.2	25.0	+ 8.6	- 17.6	22	Weather ships	(all cases)
18,600	62.0	55.0	41.9	+ 15.5	8	Oceanic Group	Ships Valentia Camborne

Comparison of the cases in Table 3 with Table 2 brings out chiefly the great difference of behaviour of surface temperature over the ocean and at inland stations including in the British Isles. The greatest standard deviation was in surface temperatures at inland stations with 16,800ft. thickness, namely 11.2°F., whereas the S.D. of surface temperature at oceanic stations was under 3°F. alike with thicknesses of 16,800 and 18,600 ft.

Table 4 presents a survey of the behaviour of the freezing level in all the cases covered by Table 2.

/Table 4.

Table 4. Observed freezing levels with particular 1000 - 500 mb. thickness values.

1000-500 mb. Thickness ft.	Average level of (lowest) 0°C. Isotherm	S.D.	No. of Cases	Lowest observed 0°C. isotherm	Highest observed 0°C. isotherm	Percentage of all cases examined which showed double or triple freezing levels.
16,880	Surface	-	18	Surface	960 mb.	0
17,400	915 mb.	37mb.	160	Surface	850 mb.	4.4
18,000	770 mb.	34mb.	41	860 mb.	710 mb.	12.2
18,600	635 mb.	21mb.	74	670 mb.	570 mb.	2.7

Summarizing, we find that the thickness value alone will give us the temperature at any given height in the free air to within 3°F., and the freezing level to within about a thousand feet, in a considerable majority of cases over the European and Atlantic region.

3. The freezing level criterion for rain or snow. The height of the freezing level above the ground and the thermal structure of the lowest few thousand feet of the atmosphere largely determine whether snow can reach the ground. A brief survey of this point is essential before proceeding further.

R. Murray (1952) examined the occurrence of rain (and rain showers) or snow (and snow showers) with various freezing level heights in the British Isles and found that frozen and unfrozen forms become equally likely when the freezing level is about 1,000 feet. This figure seems quite generally applicable to continental and oceanic locations.

The problem is however complicated somewhat for the forecaster by time-variations of freezing level within one air-mass. Quick, erratic variations of several hundred feet occur in instability showers; these are usually fleeting, but under favourable circumstances a new snow carpet may result from showers starting with a general freezing level above 1,000 feet. Douglas (1950) noticed that long-continued rain and sleet falling through dry air may so cool the atmosphere that the freezing level drops by as much as 4,000 to 5,000 feet (forming a deep isothermal layer about 0°C.) and snow ultimately reaches the ground. Widespread snowfalls in southern England began in this way on 26.12.1927 and 1.11.1942; the same effect is both frequent and important in central Europe where low relative humidities favouring evaporation cooling are much commoner than in England.

These considerations come into play with 1000-500mb. thicknesses from 17,100 feet up to 17,500 or, at most, 17,600 ft. in connexion with snowfall over regions of general elevation less than 100 to 150 metres (300 to 500 ft.).

4. The thickness criterion for snowfall: precipitation in frozen and unfrozen forms. R. Murray (loc. cit.) statistically examined the occurrence of precipitation in frozen and unfrozen forms with various thicknesses of the 1000-500 and 1000-700mb. layers at or near seven British upper air stations (Lerwick, Stornoway, Aldergrove, Leuchars, Liverpool, Downham Market and Camborne). Grouping these stations together inevitably masked the differentiation we have noticed between inland/continental and oceanic localities, most of his chosen stations being classable as oceanic. Murray found that rain and snow were equally likely when the 1000-500 mb. thickness was about 17,140 ft. or the 1000-700 mb. thickness about 9,120 ft.: these figures prove to be fairly typical of oceanic (Gulf Stream water) situations. Evidence of generally rather higher thickness values for the changeover from rain to snow may be detected in a recent paper of the Meteorological Research Committee on cold pools by Sumner (1952), who found a "fairly distinct separation" when the minimum thickness in the cold pool was about 17,200 feet.

/To

To establish the most general possible criterion, based upon a broader survey, the present investigator tabulated all cases of precipitation reported during the winter 1950/51 at the time (including precipitation in the last hour) and in the neighbourhood of the radio-soundings at Lerwick, Aldergrove, Liverpool (surface observations from Manchester, Ringway), Downham Market (Mildenhall), Berlin (Templehof), Riga, Stockholm and Oslo (Fornebu). These are all low-level stations, less than 300 feet above mean sea level; they comprise one oceanic location (Lerwick), various inland districts of the British Isles and several typical European continental locations. The mean latitude of the stations used is 56°N. The months examined were November 1950 to April 1951 inclusive for the British stations and October 1950 to April 1951 inclusive for the others. In addition the precipitation forms at one higher-level station in the British Isles, Eskdalemuir (794 ft. A.S.L.), were studied in relation to the contemporary 1000-500 mb. thickness values over the station taken from the published Daily Aerological Record.

In all there were 2,045 observations with precipitation to be classified.

The separate frequencies of rain, drizzle, snow, sleet, hail and showers of each type, also the total frequencies of precipitation of showery character, occurring with thickness ranges 17,960-18,050, 17,860-17,950 and so on down to 16,860-16,950 feet were examined for each of the nine stations named and in each month of the winter. Some of the results are shown in the histograms reproduced in figs. 2(a)-(f), in which sleet and hail are counted in with the frozen forms and shower frequencies include <u>all</u> forms of showers. Results for the whole collective and the more important variations may be summarized as follows:-

(a) <u>Rain or frozen forms.</u> In general the changeover was commonest with thickness about 17,300 feet, at which figure frozen and unfrozen forms were equally frequent.

Over the warm waters of the North Atlantic Drift as at Shetland (water surface temperatures in winter about 10°C.(50°F.)) and the coastal places in the British Isles studied by Murray, the changeover occurs about 17,150 feet. In such situations snow only falls in air which is unstable (or nearly so) from the surface up.

Over already extensively snow-covered terrain, as at Oslo, Stockholm and Riga in the depth of winter, snow is as likely to fall as rain with thicknesses 17,400 to 17,450 ft. or even higher.

The critical thickness at inland stations in the British Isles and at Berlin approximated <u>either</u> to values typical for Oslo-Stockholm-Riga or to the Atlantic group according to whether there was extensive snow lying or not.

Snow (or sleet) which fell with the higher thickness values, and all cases of snow with thicknesses over 17,700 feet, were associated with considerable inversions of temperature or deep isothermal layers and the precipitation may be presumed to have originated in a stratus or stratocumulus cloud-sheet below the stable layer. It is thought that in all cases with thicknesses of 17,700 feet or more, the ground was already snow-covered. Cases which appeared to substantiate this as a general rule were noted in such unlike regions as Aldergrove (N. Ireland) and Oslo.

Data were insufficient for any thorough examination of variation with height of the liability for snow rather than rain with different 1000-500 mb. thickness values. The results for Eskdalemuir (about 800 feet above sea-level) gave a more "blurred" criterion than for the low-lying stations examined and may have been as much affected by frequent occurrence of widespread snow lying over the Southern Uplands region in which the station lies as by its altitude.

/(b)

(b) Sleet. Sleet was common only over a small range of thicknesses around the for-the-time-being critical value for rain or snow. A few occurrences of sleet were noted with thicknesses as low as 17,100 feet at both Lerwick and Stockholm. Sleet may also occur with thicknesses up to 17,700 feet; but in the higher thickness ranges a clear-cut division between snow and rain is more usual, depending on whether the precipitation originates below the inversion or above it.

(c) Hail. Hail was rare or unobserved in winter at all the inland and continental stations. When it did occur it was only small hail, falling with any thickness values below 17,600 feet. On the other hand the larger forms of hail, such as occur in the Mediterranean area and Atlantic coasts in winter and inland in the British Isles in summer, are known to occur with 1000-500mb. thicknesses up to 18,000 feet or above.

(d) Drizzle (including supercooled or freezing drizzle). Drizzle was observed with 1000-500 mb. thicknesses as low as 17,000 feet in the British Isles and 17,100 feet in the Baltic region. Presumably drizzle may occur at any temperature which is not too low to permit enough supercooled droplets of suitable size to form in low cloud or fog. The relative frequency of drizzle increased with increasing thickness (cf. fig. 2(a)).

(e) Showers. At Lerwick, Aldergrove and Eskdalemuir, where the influence of the Gulf Stream water is strongest, showers became more frequent the lower the thickness. At continental and inland stations the maximum frequency of showers occurred with thicknesses about 17,300 feet. Lower thickness values were mostly associated with continental air which was either too dry or too stable in the lower layers to give showery precipitation.

Table 5 gives a survey of the results for all the stations examined for the winter period December 1950 - February 1951 and shows the main groupings.

Table 5. 1000-500mb. thicknesses (in feet) accompanying rain or snowfall at various stations (December - February)

Station	Value giving equal likelihood of rain or snow	Highest thickness with snow	Lowest thickness with rain	Remarks
Lerwick	17,150	17,400	17,100	Sharp changeover
Eskdalemuir	17,550	17,700	17,100	No sharp criterion
Aldergrove	17,300	17,700	17,100	Fairly sharp changeover
Manchester	17,300	17,600	17,200	- ditto -
Mildenhall	17,300	17,400	17,200	- ditto -
Berlin	17,300	17,700	17,100	- ditto -
Oslo	17,400	17,700	(17,300)	Less data than for above stations
Stockholm	17,400	17,700	17,200	Sharp changeover
Riga	17,600	17,700	(17,300)	Data insufficient

(f) Seasonal differences. Monthly data for individual stations were generally too scanty to reveal anything significant. Various groupings, such as the monthly trends of critical thickness values at oceanic and continental stations, were looked at. No seasonal trend emerged, apart from an evident requirement of really low thicknesses (17,200 ft. or below) for late spring snow and sleet in the British Isles from about mid-April onwards. This observation is doubtless related to rising sea-surface temperatures and increasing remoteness of the sources of cold air. Exceptionally early snowfall in autumn might be expected to demand similar conditions.

/(g)

(g) Geographical range. The main differentiation noted under (a) was between oceanic and continental locations and as to whether a snow-cover already existed or not. Subject to this distinction, the criteria for rain or snow (but not for hail) on low ground should have world-wide application.

As a check, 1000-500 mb. thicknesses over Malta, lying outside the normal limit of snowfall at the southern fringe of Europe, during winter 1952/53 were tabulated. The island is small and the surrounding water has a surface temperature in winter of about 13°C.(55°F.). The lowest thicknesses observed, 17,250 to 17,500 feet, were associated with cold rain and on several days in January with wet sleet falling at points over 200 feet above sea level. Snow was not observed. Hail with stones up to 1 cm. diameter fell with thicknesses ranging from 17,500 to 18,000 feet.

5. Association between the limit of an established snow or ice surface and 1000-500 mb. thicknesses in the atmosphere. A snow or ice surface has a very different effect upon the air over it from that of either dry or moist land or deep water. The diurnal range of temperature of the actual surface, whether of snow or of extensive sea-ice, is large and of the order of that of dry ground. The surface radiates out heat approximately as a black body, but a high proportion of incoming radiation is reflected and lost. The maximum temperature of the surface cannot in any case rise above 0°C. until the snow or ice is removed, a process delayed by the requirement of much latent heat to be supplied from the air, from warm rain, from the underlying soil (or water) or by direct insolation.

Studies of ablation suggest that invasions of mild air over extensive snowfields in northern Europe in winter, typically accompanied by screen temperatures of the order of +3°C.(37°F.) at a height of 4 feet above the snow, normally thaw about 1 inch of snow in 24 hours, if there is no rain or drizzle; the ablation increases to about 2 to 4 inches in a day if accompanied by appreciable rainfall.* Disappearance of 6 or 8 inches of snow may be expected to require either a continuous supply of mild air of several days' duration or a fall of an inch of rain or more.

Composite maps showing the position of the snow-limit on successive days indicate that this limit behaves in such a way that rapid advances, often on a wide front, are followed by periods of stability or of more gradual retreat in which certain segments only of the snow margin are lost at any one time.

The rapid advances result from passage of a single depression or invasion of a single cold airmass giving instability showers. The process described in an earlier section whereby long-continued precipitation chills air that was formerly rather mild and dry is also liable to result in important advances of the snow margin over previously bare ground.

Withdrawals of the snow margin follow all types of ablation. In central and northern Europe, including the British Isles, warm rain is the most effective agent for removing snow-cover in winter. At other seasons, and in regions south of about 45°N even in winter, sunshine is most effective.

Positions of the snow limit which coincide more or less with a mountain barrier are more liable to persist, when warm air advances over the high ground (and commonly fails to descend to the low ground on the lee side), than positions anywhere over the European lowlands where no barrier exists. The effect is sufficiently obvious in the way the course of the mean 0°C. surface isotherm over Europe follows the topography, with several successive weekly or monthly positions remaining close to the Norwegian and central European massifs. The greater frequency of snow lying everywhere over northern and eastern England east of the main watershed compared with the same levels on the western side (Manley 1947) is also at least partly attributable to this cause.

/Extensive

Footnote * See for instance Champion (1950 and 1951).

Extensive snow lying cools warm air passing over it in a largely similar manner to the case of warm air in summer over the Arctic ocean and other cold-water regions (downward eddy-flux of heat) (cf. Taylor 1914, Sverdrup 1936, Scherhag 1937). Over winter snow there may be, additionally, important radiation cooling from the top of fog and stratus formed in the mild air. Where the snow limit coincides with a mountain barrier, any forward thrust of warm air may be lifted above the surface and is liable to contribute frontal and orographic snowfall which adds to the depth of the lying snow.

These effects modify the air and limit the freedom of movement of the thickness isopleths.

The writer therefore decided to investigate the occurrence of various 1000-500 mb. thicknesses over established snow and ice and in the neighbourhood of the snow limit.

Positions of the snow limit over Britain and Germany were obtained by mapping actual state-of-ground reports. The number of cases in which the snow-limit was accurately known in this way was augmented, for the purpose of the tests, by many other cases in which the position of the limit could be deduced beyond reasonable doubt, to within 100 miles, from consideration of the reported sequence of weather for a week or more and the behaviour of the surface air temperatures. The last-named are particularly revealing whenever a broad warm airstream encounters lying snow and a stationary belt of sharp fall of surface temperature to +3°C. (37°F.) or lower in the moving airstream marks the snow limit. This reasoning frequently made it possible to place the snow margin in many parts of Europe and N. America. Composite maps were then drawn showing successive daily positions of the limit of snow and ice.

(a) Thickness values at the limit of snow - and ice - covered surface. For this test reported 1000-500 mb. thicknesses and values estimated from the isopleths were taken at points over the western and southwestern limit of contemporary snow-cover in Europe between 45 and 60°N, care being taken to choose points where the snow edge was fairly straight and free from deep embayments. Points used were in west Norway, western Britain, France, Germany, Poland or Sweden in a region well covered by upper air observations. Over 80% of the points chosen were on ground less than 300 feet (100 metres) above sea level, the remainder being at the edge of a mountain barrier; in neither case did it appear necessary (either a priori or in the light of results obtained) to make any allowance for the elevation of the actual test point, so long as all the low ground (below 300 ft.) to leeward was snow-covered. The region studied was also entirely within the zone of prevailing westerly winds aloft: any association found between the thickness value and the windward limit of snow-covered land (in the sense of the prevailing upper westerlies) would therefore be liable to imply some distortion of the atmospheric circulation aloft.

The mean value of 1000-500 mb. thickness given by 1,053 observations over the best attested positions of the snow limit in this European region on 99 different days between January 1947 and February 1952 was 17,297 feet, the standard deviation being about 170 feet.

This figure should be compared with normal thicknesses between January and early March in different parts of the region studied ranging from about 17,200 to 17,700 feet with a S.D. at any given place of the order of 300 feet. (e.g. mean thicknesses for Larkhill for two successive Januaries were respectively 17,460 feet S.D. 523 feet and 17,657 feet S.D. 259 feet.)

The low mean thickness and small standard deviation at the snow-limit, wherever that may happen to be, point to a real association between the snow limit and the 1000-500 mb. thickness over it and to a contemporary shift of the upper wind pattern (thermal and actual).

/Various

Various additional tests were made to broaden the basis of this result and to gain some indication of its application to other geographical regions.

The average 1000-500mb. thickness, from eighty-five radio-sonde ascents made by the Dutch whaling ship Willem Barendsz, near the pack-ice in 60°S between 12°E and 30°W (December 1946 - April 1947) in the South Atlantic was 17,260 feet S.D. 212 feet. The standard deviation might reasonably be supposed to be a little less if taken precisely at the ice margin in all cases.

As no further actual positions of the snow or ice limit were readily available, tests were made of the mean 1000-500 mb. thickness values at points on the normal position of the M.S.L. 0°C. isotherm shown by the official Russian Climatological Atlas (published 1930) for Russia and Siberia and by Bartholomew's Atlas of Meteorology (published Edinburgh 1899) for North America. The Russian and Siberian material supplied mean positions for the 0°C. isotherm at about 10-day intervals from 11th September through the winter to 1st June. The North American material yielded only monthly mean positions, which were taken as applying to the middle day of each month. The means related to the years 1849-1899 for Siberia, 1881-1915 for European Russia and 1870-1884 for N. America. An obvious weakness was that the mean positions of the 0°C. isotherm at sea level for these years had perforce to be compared with mean 1000-500 mb. thicknesses about the same date of the year for the period 1946 to 1950. In practice thickness means for seven days centred upon the relevant date were taken at each intersection of the 0°C. isotherm with the meridians of longitude, every ten degrees of longitude from 120°W to 60°W and from 20°E to 140°E. This yielded 3,268 values. The mean was 17,507 feet and the standard deviation 280 feet.

Considering the crudeness of the test, this result agrees about as closely as we could expect with the values obtained for the actual snow limit on the actual day and year. The discrepancy is likely to be due chiefly to two causes:-

(i) The 0°C. mean isotherm need not by any means coincide with the snow limit for a given period, but seems likely to protrude over bare ground somewhat beyond the snow-covered region.

(ii) The snow-cover has probably been rather less extensive in recent years, apart from the winter 1946/47 in the European sector, than in the nineteenth century.

From these tests it seems fair to conclude that the mean 1000-500 mb. thickness over the contemporary windward limit of snow and fast ice on the polar seas is close to 17,300 feet in all parts of the world and that the variation of thickness over the snow margin is distinctly smaller than that at any place well away from the margin.

(b) Movement of warm air and incursions of various thickness isopleths over extensive snow and ice-fields. Incursions of particular isopleths of 1000-500 mb. thickness were measured in nautical miles along the path of the gradient wind. Choice was restricted to cases where the snow limit was stabilized in a given position for a period of seven days or more. Note was then made of the maximum incursion of a given thickness isopleth along the instantaneous line of surface gradient wind, the mean strength of the gradient wind along that line at the time in question, the nature of the terrain and type of weather situation.

The measurements of maximum encroachment of various thickness values above 17,300 ft. over a widespread snow- and ice-covered terrain are fully logged in Table 6. Brackets indicate extreme penetrations which were excessively short-lived. All cases which may have been complicated by

/subsidence

subsidence (deduced from anticyclonic curvature of the isobars and appropriate surface weather reports) are separately listed. Thirty-eight 7-day periods taken from six winters between 1st January 1947 and 29th February 1952 provided the required conditions for test measurements in different parts of the northern hemisphere including Alaska, Canada, Europe and western Siberia*. In intermediate cases the distance of greatest encroachment of a given isopleth over snow has been rounded upwards to the next hundred miles, whereas gradient wind (V_G in the table) has been rounded downwards to the next lower unit in tens of knots. This means that, in spite of the rather small number of cases available for study, there is an enhanced likelihood of an observation as logged in the table approximating to the greatest incursion possible. Results from the first five winters (30 weeks in all permitting 35 measurements) were first logged as a separate group and analyzed graphically to discover likely asymptotes (maximum incursions and minimum gradient winds); thereafter results for the sixth winter (8 weeks in 1951/52 permitting 12 measurements) were similarly treated and compared. The additional material from the sixth winter (about 30% of the original data considered) repeated the same pattern and pointed to substantially the same extremes.

FOOTNOTE:

* The terrains covered were of course infinitely varied and difficult to summarize. Maximum encroachments, measured either over extensive lowland (e.g. the north European plain) or over an initial mountain barrier which also marked the contemporary snow limit (e.g. the Alps and Alpine foothills), were however found to give a reasonable gradation with wind speed (Tables 6 and 7) without making any allowance for the elevation of the country.

/TABLE 6.

TABLE 6. GREATEST ENCROACHMENTS OF VARIOUS 1000-500 MB. THICKNESSES OVER SNOW AND ICE SURFACES, MEASURED ALONG GRADIENT WIND.
(All individual cases)

GRADIENT WIND AT M.S.L. / MEAN STRENGTH ALONG PATH	Distance of greatest incursion over snow/ice surface in Nautical Miles (Tabulated figures below are numbers of cases)																								
	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	2500
70 Kt.						1																				
60			1							2						(1)										
50				1						1																
40				1	2		3	1 1*	2			(1*)	(1)		1*										(1*)	((1*))
30	1		1	1			1			2	((2))	1*	1*				((1*))									
20	2	1*	1*		1						1*															
10																										
0	3	1	1*	2			1*		(47 cases in all)						INCURSIONS OF THE 17,400 FT. ISOPLETH Each case the greatest incursion in seven days.											
70 Kt.					1																					
60	1			1			1					(1)														
50	1					1																				
40	1 1*	1	1	1	3 1*	2					(1*)		1*								(1*)		(1*)			
30	3		1	1	1	1*				2*																
20		1 1*							2*																	
10																										
0	5 1*	1				1*		(45 cases in all)						INCURSIONS OF THE 17,600 FT. ISOPLETH Each case the greatest incursion in 7 days.											
70 Kt.	1																									
60	2				1	(1)																				
50	2																									
40	6 2*	1		1	(1*)						1*															
30	4 1*								1*																	
20	2 2*		1*	1*																						
10																										
0	6 2*						(39 cases in all)									INCURSIONS OF THE 17,800 FT. ISOPLETH Each case the greatest incursion in 7 days.											
70 Kt.																										
60	4																									
50	2																									
40	7 3*						((1*))																			
30	3 2*																									
20	1 4*																									
10																										
0	6 2*						(36 cases in all)									INCURSIONS OF THE 18,000 FT. ISOPLETH Each case the greatest incursion in 7 days.											

NOTE: Cases complicated by subsidence, indicated by anticyclonic curvature, are shown with an asterisk.
( ) means maximum incursion maintained for less than 48 hours.
(( )) means maximum incursion lasted under 12 hours.

We conclude from this table that:

(i) Thicknesses of 18,000 feet do not transgress at all over extensive snowfields without the aid of subsidence*.

(ii) Thicknesses of 17,800 ft. do not encroach more than about 500 nautical miles over snow without the aid of subsidence.

(iii) For thicknesses of 17,400 feet the maximum incursion is some 1,500 nautical miles without subsidence, but may reach 2,500 miles or more for a short time when subsidence is occurring.

In all cases the final limitation on greater incursions appears to be imposed by the improbability of gradient winds of the requisite strength being maintained over the necessary distances.

Table 7 lists the maximum encroachment* of the various thickness isopleths indicated by graphical analysis of the cases in the Table 6. (Figures in brackets are rather free estimates; hyphens have been entered where no estimate was justified by the data available.) The effect of subsidence or no subsidence may be clearly seen. A third column shows the result of singling out cases where the snow limit was stabilized near a mountain barrier athwart the path of invading warm air.

Coincidence of the snow limit with an orographic barrier (which need not be more than 1000 metres in height) may have a decisive effect. The right-hand column in Table 7 includes cases of snow limits stabilized at the Alps and Rocky Mountains, at the Norwegian highlands and in two cases at the Pennine and Welsh hills in Great Britain. In all these cases there were no incursions at all, even of the 17,400 ft. thickness isopleth, over the snow with less than 30 kt. winds advancing warm air over the barrier; maximum encroachments were enormously reduced even with a major thrust of warm air and high values of mean gradient wind.

/Table 7.

FOOTNOTE 1

* 18,000 feet is believed to be also about the maximum thickness observed over the inner Arctic basin in Summer at the time of gradient loosening of the pack-ice on the polar sea.

FOOTNOTE 2

* Mean maximum encroachments during a 7-day period of stabilized snow-limit for various gradient wind strengths and the absolute maximum encroachment of each thickness isopleth.

Table 7. Maximum encroachment of given thickness lines over extensive snow and ice, measured in nautical miles along the air stream. (From graphical analysis of the figures in Table 6.)

V_G (Knots)	Cases with subsidence	All Cases without subsidence (Nautical Miles)	Cases without subsidence where snow-limit was stabilized near a topographical barrier.
			17,400 ft. thickness
0	800	250	0
15	1,200	500	0
30	1,800	1,000	130
45	2,400	1,200	(400)
ABS. MAX.	2,400	1,500	900
			17,600 ft. thickness
0	500	under 200	0
15	900	250	0
30	1,500	450	under 100
45	2,200	750	-
ABS. MAX.	2,200	1,100	500
			17,800 ft. thickness
0	250	0	0
15	450	under 200	0
30	900	200	0
45	(1,400)	350	under 300
ABS. MAX.	-	500	300
			18,000 ft. thickness
0	0	0	0
15	(200)	0	0
30	(400)	0	0
45	(600)	0	0
ABS. MAX.	-	0	0
Numbers of cases used	11	24	12

(c) Advance of cold air and movement of various thickness isopleths over bare ground and ocean waters beyond the snow limit. The warming of cold air over the sea has been studied by Craddock (1951) and others, and their work need not be repeated here.

Movement of the thickness isopleths for values below 17,300 ft. beyond the snow and ice margin was however briefly studied. Such movements over land are nearly always accompanied by advances of the snow limit itself. Over open ocean no such rapid changes in the distribution of frozen surface are possible. Indeed at certain times forward thrusts of cold air accompanied by high, stormy winds may cause a good deal of ice to break adrift and bring about some withdrawal of the effective ice margin.

Examination of movement of various thickness isopleths over the oceans north of 50°N yielded the following results:-

(i) Movement of the 17,400 and 17,200 ft. isopleths appears unlimited except in the southerly direction.

(ii) Extreme advances of the 17,000 ft. isopleth over the ocean may be limited to about a thousand nautical miles with extreme winds south of latitude 60°N, but are apparently unlimited farther north.

/(iii)

(iii) 16,800 ft. thickness was not observed more than 800 nautical miles from the ice margin, except north of latitude 60° where greater advances over open water occur with high winds.

(iv) 16,600 ft. and lower thickness values were not observed at all away from the ice, save with winds of over 50 kt. and in latitudes north of 60°N.

(v) The 16,200 ft. isopleth in no circumstances advanced more than 400 nautical miles from the ice.

These conclusions are based on tests in just 33 different weeks of clearly identified ice margin during six winters (1947-52).

6. Summary of results and concluded implications.

(a) Results.

(1) We have found a fairly regular changeover of precipitation from unfrozen to frozen forms with 1000-500 mb. thickness about 17,300 ft. Over already established snowfields the normal thickness value for the changeover is rather higher, about 17,400 to 17,450 ft. Over seas and oceans with surface water temperature about 10°C. the average thickness value for the changeover from rain to snow is lower, about 17,150 ft. In extreme cases the changeover may come with any value from 17,100 to 17,900 ft., but in most circumstances 17,300 ± 150 ft. (5,280 ± 45m.) is the critical thickness. (The variations depend greatly on lapse rate of temperature in the lowest 1 to 2 km., but also on whether the precipitation is formed in the cloudmasses of the friction layer or at higher levels).

(2) The average 1,000 - 500 mb. thickness at the windward limit of extensive snow and ice is also found to be just 17,300 ft. with a standard deviation only about two-thirds of that characteristic for specific points normally far away from the snow/ice margin.

(3) Movement over extensive snow of the thickness isopleths for values of 17,400 ft. and higher is subject to certain restrictions. Many sorts of cooling processes are involved.

(4) When the windward limit of the snow is protected by an orographic barrier from invading warm air, advance of the higher thickness values is much more restricted. Correspondingly, in these cases, the snow-cover is more likely to persist and continue restricting the movement of the upper air pattern. Invading warm fronts are also liable to be held up and occluded at the snow-margin where this is fortified by mountains (on occasion even the hills of the British Isles) - a process which commonly yields more snow.

(5) Warming over open sea sharply restricts the movement of isopleths of the lower thickness values, when cold air thrusts out beyond the snow/ice limit. Similar forward thrusts of cold air over land usually spread the snow-cover itself to new limits.

(6) The evidence suggests that extensive snow lying itself plays some part in maintaining the cold trough in the upper troposphere which favours persistence of the snow. A snowfield of 1,500 nautical miles west to east extent - i.e. fifty degrees of longitude in 60°N or thirtyfive degrees of longitude in 45°N - would be sufficient, while it lasted, to cause a trough in the 17,400 ft. isopleth of 1000-500 mb. thickness, unless advection of warm air at an average velocity of 50 knots or more were maintained across the entire 1,500 miles or appreciable subsidence were at work. In most cases a broad trough in the thickness pattern would result. Moreover, consideration of the distribution of normal thickness values over

the northern hemisphere shows that in mid October, when the first extensive snow-deck is established over much of northeastern Canada and over eastern Asia north of the Mongolian plateau in 50-55°N, the associated cold troughs should bring the thickness down to 500 to 800 feet below the values at that time ruling over the (eastern) North Atlantic and (eastern) North Pacific oceans in the same latitude. As the winter progresses, these major cold troughs grow in longitudinal extent and in intensity and are thrust farther south, till widespread snow reaches latitude 40 to 45°N over parts of N. America and Asia in January.

These results have an obvious bearing upon the much debated question of the primacy of thermal or orographic influences in the general circulation of the atmosphere (see, for instance, Sutcliffe 1951). The investigation itself has provided instances of the effectiveness of both these factors as partial controls acting upon the circulation in the upper troposphere.

(b) Further implications. Several corollaries throw new light on known facts of meteorological experience:-

(1) For the occurrence of exceptionally prolonged and severe winters in the British Isles, the development of a continuous snow-cover right across Europe north of the Alps and Carpathians (and abnormal cooling of the North Sea surface) must be important. A snow mantle over the British Isles and western fringe of Europe alone, such as sometimes results from outbursts of maritime Arctic air from the Norwegian Sea, has far too little longitudinal extent to exercise any decisive cooling upon the atmosphere or appreciably to restrict the eastward advance of a procession of ridges and troughs in the upper westerlies. Cases of this occurred in 1944/5, 1951/2 and 1952/3, and the snow abruptly disappeared in mid winter, followed by persistently mild westerly, spells.

(2) Baur (1950) found that for Berlin winters in which the first half of December was $2\frac{1}{2}$°C. milder than normal were invariably mild winters. Development of a widespread snow-sheet across Eurasia to near Berlin by that date is likely to be a necessary, though not a sufficient, condition for persistent severe weather in western Europe.

(3) A broad continental snow-cover, as over the northern continents in winter, must favour an upper air pattern with a great warm ridge near, and just outside, the western limit of the snow and a broad cold trough over the snow. Variations of detail on this basic upper air pattern are likely to produce repeatedly situations favouring anticyclogenesis near (and over) the northwestern portion of the snow-covered region and cyclogenesis just outside the eastern or southeastern limit.

(4) An established continental snow-cover in any winter may be expected to encourage the steering of depressions along its perimeter, including southeastward-moving systems near the western limit of the snow - cf. also attempted reconstructions of ice-age phenomena by Simpson (1934) and Manley (1951).

(5) Restrictions imposed by extensive snowfields on free movement of the thickness isopleths must limit the possibilities of any radical change of depression tracks unless and until a sufficiently vigorous pulse of warm air advection removes the snow.

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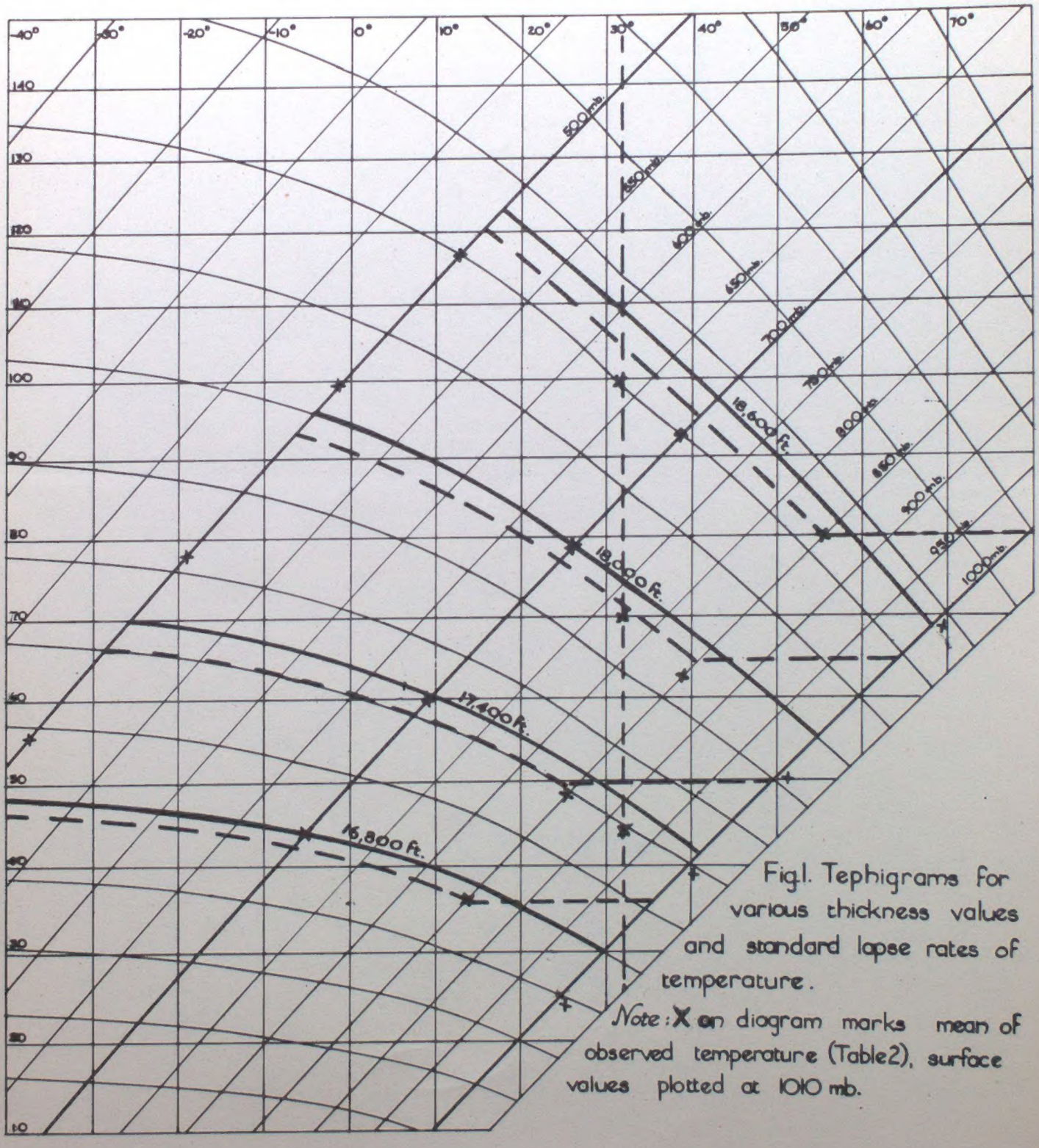

Fig.1. Tephigrams for various thickness values and standard lapse rates of temperature.

Note: X on diagram marks mean of observed temperature (Table2), surface values plotted at 1010 mb.

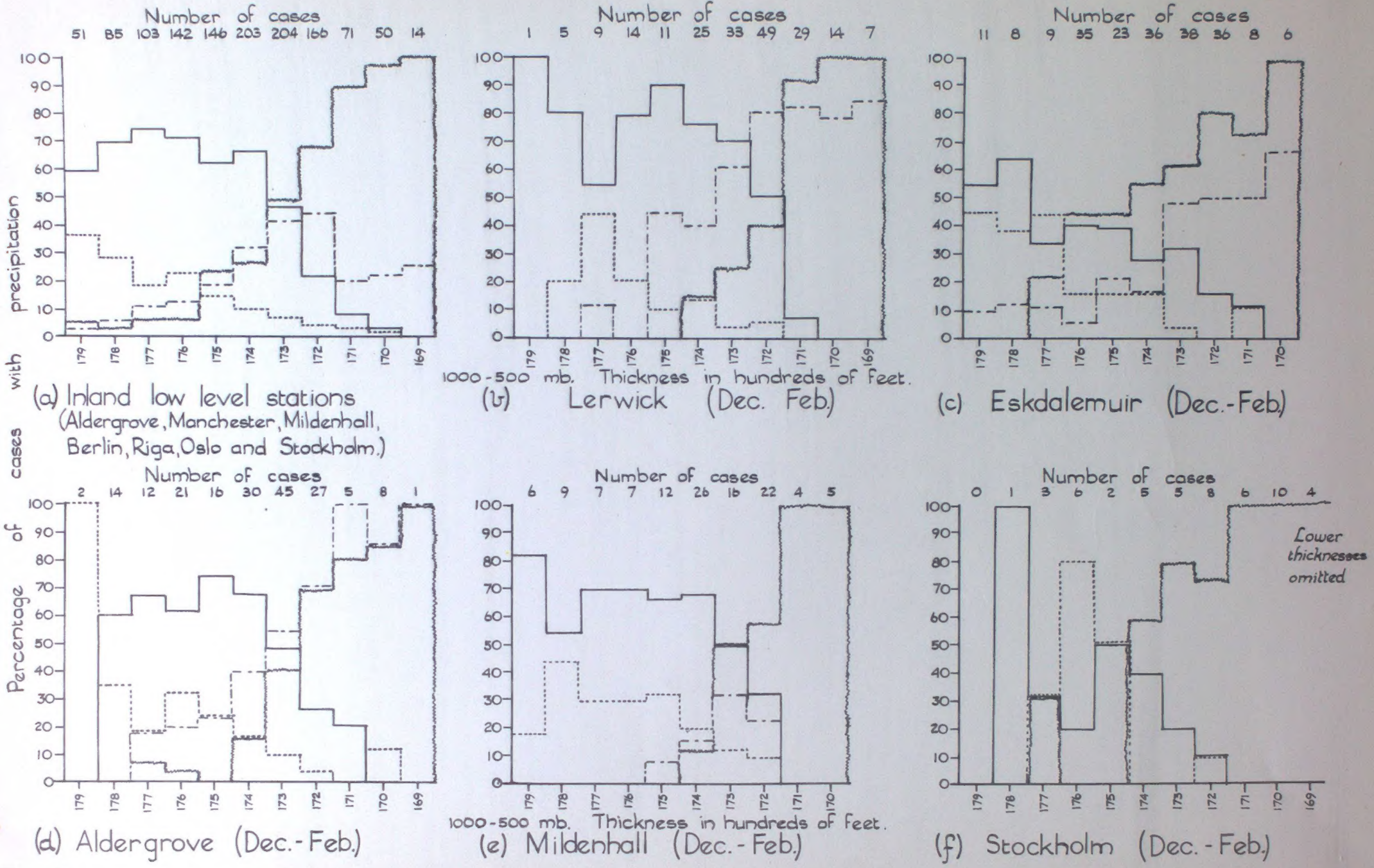

Fig. 2. Key: —— Rain ····· Drizzle ——— Frozen forms (including sleet and hail) -·-·- Showers (of all forms).